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EXTINCTION CHARACTERISTICS OF PYROTECHNICALLY-GENERATED ALKALI-HALIDE SMOKES

by

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Background

Under Contract No. N00019-81-C-0125 with the Naval Air Systems Command (AIR 310C), Calspan Corporation continued its experimental investigation of hygroscopic aerosol smokes, a collaborative investigation with several Navy laboratories now in its fourth year. The overall objective of the NavAir 310 program is the development of an effective screening agent to both visible and infrared wavelengths utilizing pyrotechnically-generated hygroscopic aerosol.

For a number of years, NWC-China Lake has been working on development of such pyrotechnical[illegible]erated screening agents based on their original CY85A pyrotechnic. The[illegible] pyrotechnics are formulated to produce smokes of alkali-halide salt particles upon combustion. The primary advantage of such pyrotechnics is their ability to produce copious numbers of hygroscopic aerosol, which, when exposed to a sufficient level of ambient humidity, deliquesce to form solution droplets of approximately twice their original size and five times their original mass. Thus, only a fraction of the resultant cloud mass (smoke screen) originates from the pyrotechnic, the remaining mass being supplied by atmospheric water vapor. A number of formulations, each a variation from the original CY85A composition, have been produced. Calspan's efforts for the previous three years have been concerned primarily with measurement of the visible wavelength extinction, size distribution, aerosol growth characteristics, and mass yield of three of these pyrotechnics (CY85A, NWC 29, and NWC 78).

Objectives of Present Program

This year's effort, reflecting the Navy's increasing interest in IR wavelength transmission, was primarily concerned with the evaluation of the IR extinction effectiveness of six NWC pyrotechnics: CY85A, NWC 29, NWC 78, NWC 79, NWC 90, and NWC 164. The specific objectives of this year's effort were:

1. Through a series of large-scale chamber tests, determine, as functions of humidity, IR and visible wavelength extinction and mass yield of the pyrotechnics.

2. Determine the chemical composition of the pyrotechnic aerosol smokes.

3. Investigate and define any particle size-particle chemical composition relationship.

4. Through individual particle growth analyses, evaluate the deliquescent growth characteristics of a number of pure and mixed laboratory salts.

Summary of Major Results

Results from the chamber tests indicate that at high humidities (∿90% RH), all six of the pyrotechnics produce approximately the same extinction. At 75% RH, however, relative to CY85A, any of the other five pyrotechnics provide about four times greater extinction than is obtained with CY85A. This was found to be due to improved deliquescent growth characteristics of the other pyrotechnics relative to CY85A. At low humidities (∿40% RH), the NWC 90 and 164 pyrotechnics appear to provide greater extinction at IR wavelengths from 7-14 μm relative to the other pyrotechnics; however, additional tests are required to verify this conclusion. Increased IR extinction in the NWC 90 and 164 smokes at low humidities may be the result of absorption by graphite particles present in their smokes.

Examination of pyrotechnic smoke particles, in the size range 0.2-1.0 μm, indicated no significant relationship between a particle's size and its chemical composition for any of the six pyrotechnics. (However, analyses did not include assessment of the graphite particulates of the NWC 90 and NWC 164 smokes.)

All of the above topics are discussed in greater detail within the body of this report. Section 2 describes the chamber facility and instrumentation, and outlines test procedures. Results from the chamber tests are presented and discussed in Section 3. Section 4 is devoted to the laboratory study of the growth of pure and mixed salts. Section 5 provides a summary of the major findings presented in this report and specific recommendations resulting from this study.

Definition of terminology used to describe the extinction characteristics of the pyrotechnics is presented in Appendix A. Appendix B presents a limited comparison of the NWC alkali-halide smokes to white phosphorus.

Section 2
FACILITIES AND PROCEDURES

2.1 Facilities and Instrumentation

The laboratory investigation was carried out in Calspan's 600 m^3 chamber. The facility's large size (~9 m diameter by ~9 m high) minimized wall effects, allowed relatively long path lengths for extinction measurements, and provided for a useful aerosol lifetime of many hours. A complete air handling capability permitted the removal of virtually all particulate and gaseous contaminants prior to each experiment, the introduction of specified aerosols, and control of humidity from ~30 to 97% RH. A cut-away view of the chamber facility is presented in Figure 1.

Instrumentation used to monitor aerosol behavior within the chamber included visible and IR wavelength transmissometers, a Thermo Systems Model 3030 Electrical Aerosol Analyzer (EAA), and MRI Integrating Nephelometer, a Gardner Associates Small Particle Detector, and a Royco Optical Particle Counter. Specific details of the instrumentation and chamber facility may be found elsewhere (e.g., Mack et al, 1978).

Extinction of electromagnetic radiation by aerosol hazes was measured at visible wavelengths over a path of 2.64 m. A lense collimated beam from an incandescent bulb powered by a regulated power supply was focused on an RCA 4440 photomultiplier detector. The photomultiplier has a peak sensitivity in the range 0.4-0.5 μm wavelength. The optical transmissometer system has been used in the chamber for years and displays good stability over periods of about 1 hour, with a resolution of about 2-3 percent.

The IR transmissometer utilizes an 18.3 m pathlength, a 900°C black body source, and an HgCdTe detector operated at liquid nitrogen temperature. The source beam, chopped and collimated, is directed through the chamber (at a height of ~1.5 m) and folded back to the detector by spherical front- silvered mirrors. Continuous measurements of extinction as a function of wavelength are obtained via a pair of variable wavelength filter wheels located in front of the detector. The spectral resolution of these filters is two percent over the

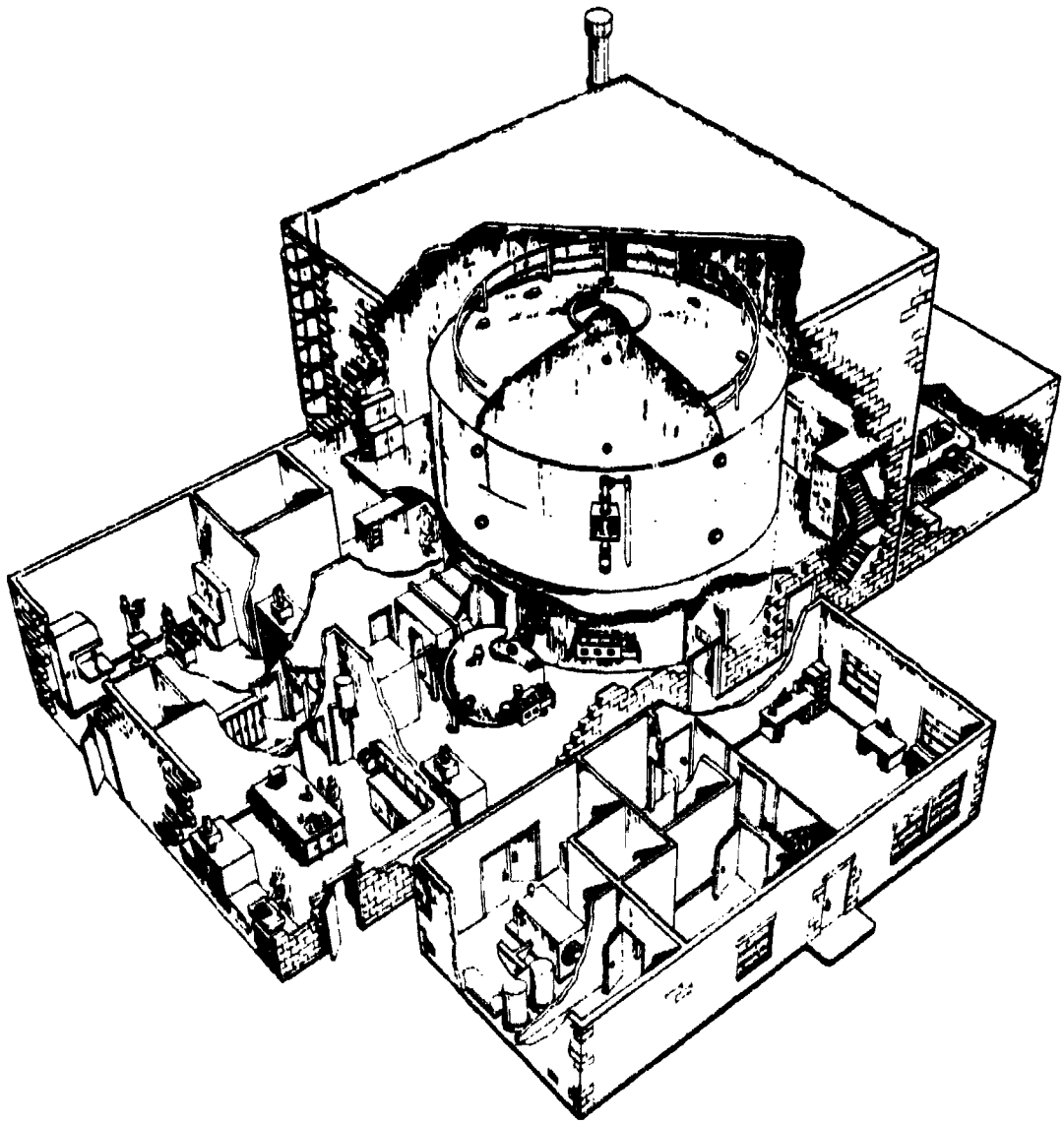

Figure 1. Cut-Away View of Calspan's Chamber Facility.

wavelength interval from 2-14 μm. Data acquisition and reduction is computer controlled. Intensity measurements are obtained at approximately 0.02 μm wavelength intervals, with a complete 2 to 14 μm scan requiring ∿4 minutes.

2.2 Production of Pyrotechnic Hazes

Production of the pyrotechnic hazes was generally accomplished as follows: After humidification of the chamber to greater than the desired relative humidity using a commercial nebulizer, all particulates were removed by absolute filters. The filtration process usually resulted in a decrease of relative humidity of about 5%. Subsequently, a specific quantity of the pyrotechnic was aerosolized in the chamber. To increase the uniformity of the burns, the pyrotechnic was ignited with a propane torch. Due to the hygroscopic nature of the resulting pyrotechnic smoke, the individual aerosol particles absorbed water until the vapor pressure of the aqueous droplets equalled that of the ambient air, producing a haze whose density at a given relative humidity was dependent upon the quantity of pyrotechnic burned. After allowing several minutes for the cloud to equilibrate, measurements were made of appropriate parameters. The hazes were continuously stirred to insure well-mixed, homogeneous conditions throughout the chamber during each experiment.

2.3 Mass Loading Samples

Mass loading filter samples were collected upon 47 mm Pallflex, Type QAST, quartz fiber filters. Samples were drawn at a rate of ∿1 cfm for 15 minutes. A newly developed technique allowed weighing the filters in the chamber environment thereby minimizing possible errors due to condensation upon, or evaporation from, the hygroscopic aerosol samples.

After weighing the mass loading samples in the chamber environment, the samples were baked at ∿110°C for one hour to evaporate all condensed water present in the sample. The sample was then immediately reweighed to obtain the mass of the dry aerosol. To insure that baking did not vaporize sample components other than water, the samples collected during low humidity

tests, for which the aerosol was naturally dry (except for a relatively small amount of condensation due to LiCl and $MgCl_2$ salts), were also baked and reweighed. No significant change in the weight of these samples occurred, indicating that only the water of condensation was being removed in the baking process.

Section 3
RESULTS OF LARGE-SCALE CHAMBER TESTS

3.1 Log of Experiments

Table 1 presents a log of the chamber experiments performed. For each experiment, the pyrotechnic, payload and RH are presented along with the type of data obtained. These data include visible and IR extinction measurements, yield measurements obtained from mass loading samples, size spectra measured by the aerosol sizing instruments*, and samples collected for analysis by scanning electron microscopy (SEM). The tests were run at normal room temperatures (18-27°C). In all, 25 experiments were performed over a range of humidity from 37 to 92% RH.

3.2 Chemical Analyses of the Obscurant Aerosols

Low volume filter samples obtained for mass-loading measurements during the low humidity tests were analyzed for elemental composition of the aerosolized pyrotechnic. Analysis for K, Mg, Na, Ca and Li was performed by atomic absorption spectroscopy. Ion chromatography was used to determine Cl content. These results, together with the chemical composition of the bulk pyrotechnic and predicted aerosol (as provided by Dr. L. Mathews, NWC, China Lake) are presented in Table 2.

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*In analyses of the size distribution data for this test series, it became apparent that the resultant size distributions were invalid. Size distribution data, therefore, are not presented. The aerosol equipment is presently undergoing factory recalibration and will be available for use in future tests.

Table 1

Log of Chamber Tests Conducted During FY81

TEST PARAMETERS				DATA OBTAINED				
Exp No.	Pyrotechnic	Payload (g)	RH (%)	Extinction VIS	Extinction IR	Mass Yield	Size Spectra	SEM Sample
1	Preliminary Test							
2	Preliminary Test							
3	CY85A	80	88	X	X	X		
4	NWC 164	80	90	X	X	X		
5	NWC 90	80	89	X	X	X		
6	NWC 79	80	90	X	X	X		
7	NWC 29	80	92	X	X	X		
8	NWC 78	80	91	X	X	X		
9	CY85A	80	73	X	X	X		
10	CY85A	80	75	X	X	X		
11	NWC 164	80	75	X	X	X		
12	NWC 90	80	75	X	X	X		
13	NWC 79	80	75	X		X		
14	NWC 29	80	76	X	X	X		
15	NWC 78	80	75	X	X	X		
16	CY85A	160	76	X	X	X		
17	NWC 79	80	75	X	X	X		
18	CY85A	80	37	X		X		
19	CY85A	.5 & 80	34	X		X	X	
20	CY85A	1 & 160	48	X	X	X	X	X
21	NWC 164	1 & 160	44	X	X	X	X	X
22	NWC 90	1 & 160	46	X	X	X	X	X
23	NWC 79	1 & 160	37	X	X	X	X	X
24	NWC 29	1 & 160	42		X	X	X	X
25	NWC 78	1 & 160	37	X	X	X	X	X

Table 2

Composition by Weight Percent of the NWC Alkali-Halide Pyrotechnics and Resultant Smoke

BULK PYROTECHNIC COMPOSITION (NWC)

	CY85A	NWC 29	NWC 78	NWC 79	NWC 90	NWC 164
Sodium Perchlorate	-	79	54	40	46	45
Potassium Perchlorate	65	-	25	29	23	22
Sodium Chloride	10	-	-	10	-	-
Lithium Chloride	-	2	2	2	2	2
Lithium Carbonate	2	-	-	-	-	-
Graphite	-	-	-	-	10	10
Magnesium	5	5	5	5	5	5
Hydrocarbon Binder	18	14	14	14	14	16

PREDICTED AEROSOL COMPOSITION (NWC)

	CY85A	NWC 29	NWC 78	NWC 79	NWC 90	NWC 164
NaCl	18.5	79	52	52	52	52
KCl	63	-	27	27	27	27
LiCl	-	4	4	4	4	4
Li_2CO_3	3.5	-	-	-	-	-
MgO	-	17	17	17	17	17
Graphite	-	-	-	-	0-20	0-20

MEASURED AEROSOL ELEMENTAL COMPOSITION (CALSPAN)

	CY85A	NWC 29	NWC 78	NWC 79	NWC 90	NWC 164
Cl	51	63	59	58	59	58
Na	6	33	23	22	23	24
K	39	<<1	15	16	15	16
Mg	3	3	3	3	2	2
Li	<1	<1	<1	<1	<1	<1

3.3 Relationship of Particle Size to Particle Composition

Based on evidence from last year's study (Hanley and Mack, 1980) suggesting a possible relationship between particle size and chemical composition in the pyrotechnic smokes, a limited evaluation of this relationship was performed for each of the pyrotechnics. Approximate particle diameter and composition (elements ≥ Na in atomic weight) were determined simultaneously via scanning electron microscopy and energy dispersive x-ray analyses, respectively. This analysis allowed for only the detection of elements present in a particle, a quantitative assessment of composition on an individual particle basis was not possible. The samples, obtained during the low humidity chamber tests, were collected upon 0.015 μm pore diameter Nucleopore polycarbonate membranes. The particle size covered in the analysis ranged from 0.2-1.0 μm; larger and smaller particles were not found in the samples. (While larger particles are believed present in the smokes, due to their low concentration relative to the 0.2-1 μm diameter particles, a cascade impaction technique may be required to adequately sample the larger (i.e., >1 μm diamter) particles.)

Table 3 presents the results from these analyses. Twenty-five particles of each pyrotechnic aerosol were analyzed; elements detected are denoted with an "X" as appropriate. It is apparent that while particle composition may vary for a given pyrotechnic, the variation does not appear to be significantly size dependent. Rather, the variations appear random. (Note that the compositional analysis did not include graphite (i.e., carbon), a known constituent of the NWC 90 and NWC 164 smokes. Since the graphite of these pyrotechnics is dispersed simply through the mechanical action associated with the combustion process (and not by a vaporization/condensation process), the size of the graphite aerosol is likely to be highly dependent on the size of the graphite particles as added to the bulk pyrotechnic mix.)

Comparison of Table 3 with Table 2 shows that the individual particle compositions are consistent with both the predicted aerosol composition and the elemental composition of bulk aerosol samples.

Table 3

SEM Analyses of Particle Composition* and Size for the Pyrotechnic Smokes

CY854					
No	Particle Diameter (um)	Na	Mg	Cl	K
1	0.1			X	X
2	0.1	X	X	X	X
3	0.2	X		X	X
4	0.2		X	X	X
5	0.2	X		X	X
6	0.2	X		X	X
7	0.2		X	X	X
8	0.3			X	X
9	0.3		X	X	X
10	0.3		X	X	X
11	0.3	X		X	X
12	0.3	X	X	X	X
13	0.3		X	X	X
14	0.3	X		X	X
15	0.3		X	X	X
16	0.3			X	X
17	0.4		X	X	X
18	0.4	X	X	X	X
19	0.4			X	X
20	0.4	X	X	X	X
21	0.4		X	X	X
22	0.8			X	
23	0.8			X	X
24	1.0		X	X	X
25	1.3	X		X	X

NWC 29					
No	Particle Diameter (um)	Na	Mg	Cl	K
1	0.2	X	X	X	
2	0.2	X		X	
3	0.2	X		X	
4	0.2	X		X	
5	0.2	X		X	
6	0.3	X		X	
7	0.3	X		X	
8	0.3	X		X	
9	0.3	X		X	
10	0.3	X		X	
11	0.3	X		X	
12	0.3	X		X	
13	0.3	X		X	
14	0.4	X		X	
15	0.4	X	X	X	
16	0.4	X		X	
17	0.4	X		X	
18	0.4	X		X	
19	0.5	X		X	
20	0.6	X	X	X	
21	0.6	X	X	X	
22	0.8	X		X	
23	0.8	X	X	X	
24	0.0		X		
25	1.0	X		X	

NWC 78					
No	Particle Diameter (um)	Na	Mg	Cl	K
1	0.2			X	X
2	0.2	X		X	X
3	0.2	X		X	X
4	0.3		X	X	X
5	0.3	X		X	X
6	0.3	X		X	X
7	0.3	X		X	X
8	0.3	X	X	X	X
9	0.4	X		X	X
10	0.4	X		X	X
11	0.4	X		X	X
12	0.4	X	X	X	X
13	0.5	X		X	X
14	0.5	X	X	X	X
15	0.5	X		X	X
16	0.5	X		X	X
17	0.5	X	X	X	X
18	0.5	X		X	
19	0.5	X		X	X
20	0.6	X	X	X	X
21	0.6	X	X	X	X
22	0.8	X		X	X
23	0.8	X		X	X
24	0.8	X	X	X	X
25	0.8	X	X	X	X

NWC 79					
No	Particle Diameter (um)	Na	Mg	Cl	K
1	0.2	X	X	X	X
2	0.2	X		X	X
3	0.2	X	X	X	
4	0.2	X		X	X
5	0.2	X		X	X
6	0.2	X		X	X
7	0.3	X		X	
8	0.3	X		X	X
9	0.3	X		X	X
10	0.3	X	X	X	X
11	0.3	X		X	X
12	0.3	X		X	X
13	0.3	X		X	X
14	0.3	X		X	X
15	0.4	X		X	X
16	0.4	X		X	X
17	0.4	X		X	X
18	0.4			X	X
19	0.4	X		X	
20	0.4	X		X	X
21	0.6	X		X	X
22	0.7	X		X	X
23	0.8	X		X	X
24	0.9		X	X	X
25	1.0	X	X	X	X

NWC 80					
No	Particle Diameter (um)	Na	Mg	Cl	K
1	0.2	X		X	
2	0.3	X		X	X
3	0.3	X		X	X
4	0.3	X		X	X
5	0.3	X	X	X	
6	0.3	X		X	
7	0.3	X		X	X
8	0.3	X		X	X
9	0.3		X	X	
10	0.3	X		X	X
11	0.3			X	X
12	0.4	X		X	X
13	0.4	X		X	X
14	0.4	X		X	X
15	0.4	X		X	X
16	0.4	X	X	X	X
17	0.5	X		X	X
18	0.5	X		X	
19	0.5	X	X	X	X
20	0.5	X		X	X
21	0.6	X		X	X
22	0.8	X		X	
23	0.8	X		X	
24	0.8		X	X	X
25	0.8	X	X	X	X

NWC 84					
No	Particle Diameter (um)	Na	Mg	Cl	K
1	0.2	X		X	
2	0.2	X		X	X
3	0.2	X	X	X	
4	0.2	X		X	X
5	0.3	X		X	
6	0.3	X		X	X
7	0.3	X	X	X	X
8	0.3	X		X	X
9	0.3	X		X	
10	0.3	X		X	X
11	0.3	X	X	X	X
12	0.4	X	X	X	X
13	0.4	X		X	X
14	0.4	X		X	X
15	0.4	X		X	
16	0.5	X	X	X	X
17	0.5	X		X	
18	0.5	X		X	
19	0.5	X		X	X
20	0.5	X		X	X
21	0.5	X		X	X
22	0.5	X		X	X
23	0.5	X		X	
24	0.6	X		X	
25	0.8	X		X	

*'X' indicates detected element

3.4 Results of Extinction and Mass Yield Measurements

Introduction

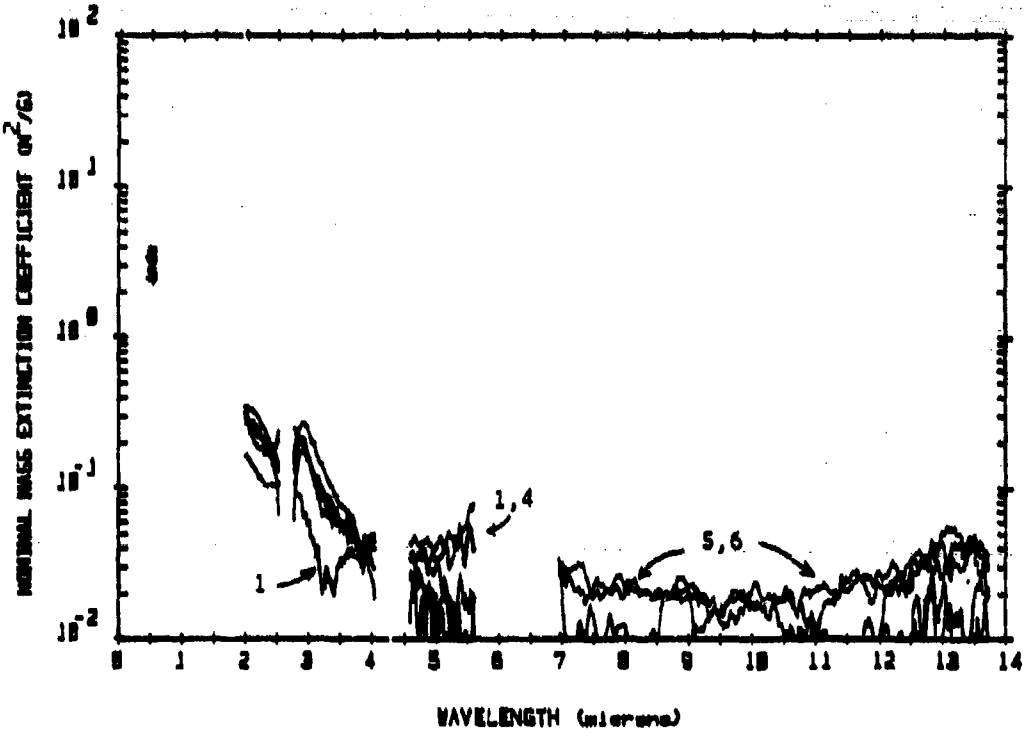
Figures 2, 3 and 4 present the visible and IR nominal mass extinction coefficient, the nominal and total pyrotechnic mass yield, and the aerosol mass growth factor for each pyrotechnic at relative humidities of approximately 40, 75 and 90%, respectively. Definition of these parameters is provided in Appendix A. Appendix B presents a limited comparison of the extinction characteristics of the NWC pyrotechnics to white phosphorus. Appendix C presents the extinction data in terms of the payload mass extinction coefficient.

As is readily apparent from Figures 2-4, all the alkali-halide aerosols have similar extinction spectra characteristics. Maximum extinction occurs at the visible wavelength followed by decreasing extinction as wavelength increases, reaching a relative minimum at ∿2.5 μm. Extinction then increases rapidly to a secondary maximum in a water absorption line at ∿3 μm. The 3 μm peak is rather narrow, and, by 4 μm, extinction has dropped about an order of magnitude. Throughout the 4-14 μm regime, extinction varies gradually with wavelength passing through an absolute minimum at ∿9 μm before beginning a moderate increase to a relative maximum at ∿13 μm. Extinction throughout the 8-12 μm band is approximately 50 to 100 times less than the visible wavelength extinction.

Below, the nominal mass yield of the pyrotechnics is examined, followed by an assessment of the relative extinction effectiveness of the pyrotechnics at the three humidity levels (∿40, 75 and 90% RH).

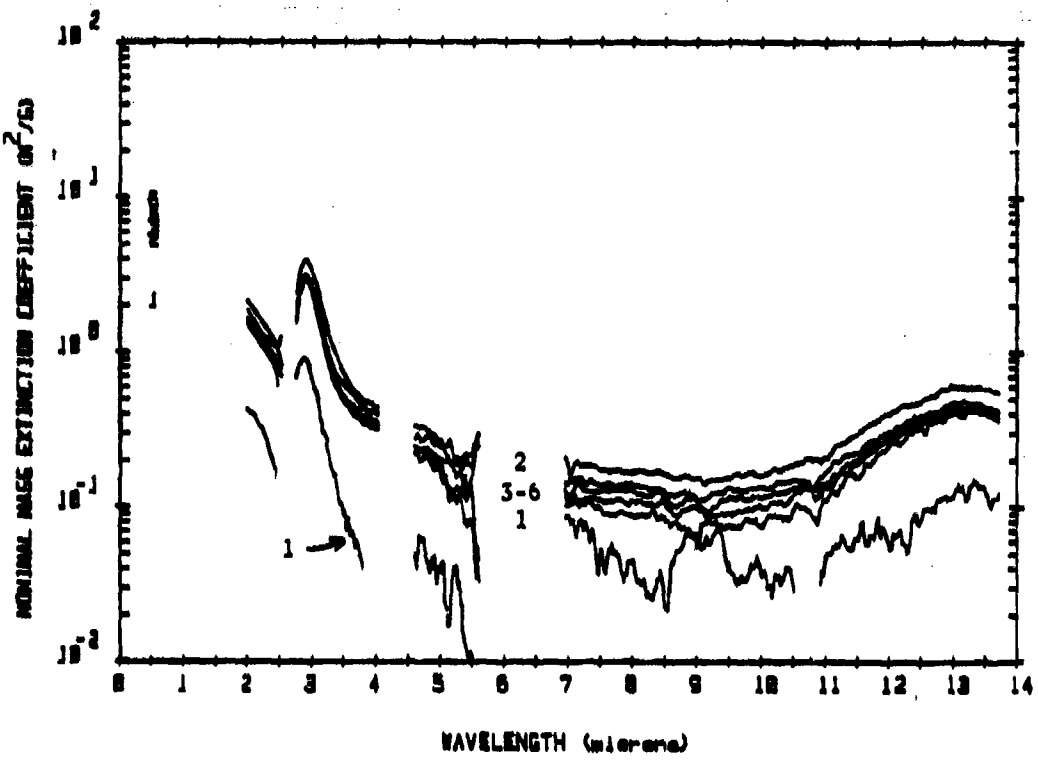
Nominal Mass Yield

When examining the nominal mass yield data presented in Figures 2-4, it is seen that the average yield of the 160 g payload tests is significantly greater than for the 80 g payloads (0.36 compared to 0.31). This suggests that the pyrotechnic dissemination efficiencies may be payload dependent, increasing with increasing payload. Realizing that in



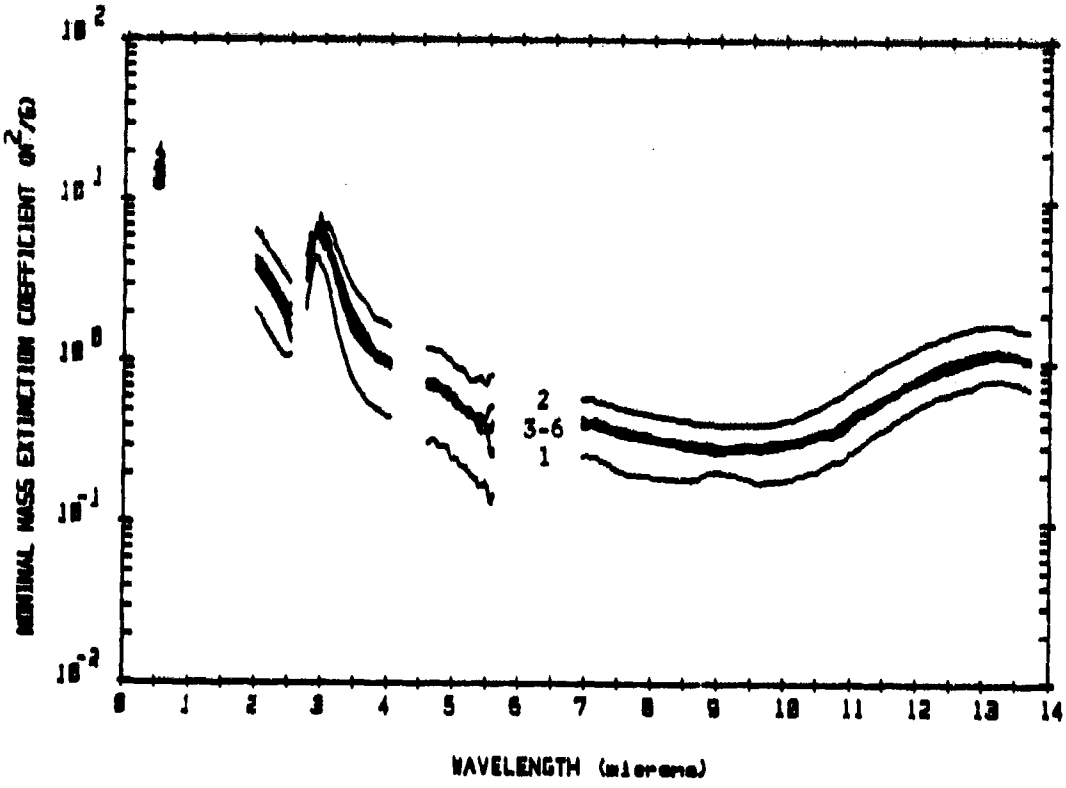
Test No.	Payload	Label	Material	RH	Pyrotechnic Nominal Mass Yield	Pyrotechnic Total Mass Yield @ RH	Aerosol Mass Growth Factor
20	160 g	#1	CY85A	48%	37%	37%	1.00
24	160 g	#2	NWC 29	42%	36%	37%	1.04
25	160 g	#3	NWC 78	37%	36%	37%	1.03
23	160 g	#4	NWC 79	37%	34%	35%	1.03
22	160 g	#5	NWC 90	46%	35%	37%	1.06
21	160 g	#6	NWC 164	44%	36%	37%	1.04
18	80 g	No IR Data	CY85A	37%	30%	30%	1.00
19	80 g	No IR Data	CY85A	34%	31%	31%	1.00

Figure 2. Extinction Characteristics of the NWC Pyrotechnics at ~40% RH.



Test No.	Payload	Label	Material	RH	Pyrotechnic Nominal Mass Yield	Pyrotechnic Total Mass Yield @ RH	Aerosol Mass Growth Factor
10	80 g	#1	CY85A	75%	30%	48%	1.60
14	80 g	#2	NWC 29	76%	29%	106%	3.66
15	80 g	#3	NWC 78	75%	30%	94%	3.13
17	80 g	#4	NWC 79	75%	29%	88%	3.03
12	80 g	#5	NWC 90	75%	34%	102%	3.00
11	80 g	#6	NWC 164	75%	31%	93%	3.00
9	80 g	Overlaps #1	CY85A	73%	32%	49%	1.53
16	160 g	Overlaps #1	CY85A	76%	35%	58%	1.66
13	80 g	No IR Data	NWC 79	75%	30%	95%	3.17

Figure 3. Extinction Characteristics of the NWC Pyrotechnics at ~75% RH.



Test No.	Payload	Label	Material	RH	Pyrotechnic Nominal Mass Yield	Pyrotechnic Total Mass Yield @ RH	Aerosol Mass Growth Factor
3	80 g	#1	CY85A	88%	34%	123%	3.62
7	80 g	#2	NWC 29	92%	32%	219%	6.84
8	80 g	#3	NWC 78	91%	28%	151%	5.39
6	80 g	#4	NWC 79	90%	29%	161%	5.55
5	80 g	#5	NWC 90	89%	37%	174%	4.70
4	80 g	#6	NWC 164	90%	33%	158%	4.79

Figure 4. Extinction Characteristics of the NWC Pyrotechnics at ~90% RH.

actual field deployment, payloads may be several orders of magnitude greater than used in laboratory tests, the corresponding yields may be underestimated by the values reported here.

Using the 80 g payload data tabulated in Figures 2-4, the reproducibility of the nominal mass yield for a given pyrotechnic is found to be approximately ±.04 as indicated by the CY85A values (0.34, 0.30, 0.32, 0.30, 0.31). Thus, the differences between the nominal mass yields for equal payloads of the different pyrotechnics may be due entirely to the inherent ±.04 measurement reproducibility.

Thus, based on the apparent dependence of the nominal mass yield on payload mass, and the inherent ±.04 accuracy of the yield measurements, it appears that the nominal mass yields for all six pyrotechnics are equivalent.

Having found the nominal mass yields to be equivalent for the pyrotechnics, differences in their extinction effectiveness will be due solely to the resultant aerosol extinction characteristics. Examination of these aerosol characteristics are presented in the following section.

Extinction Effectiveness at Low Humidity (~40% RH)

At low humidities (say RH <60%), all six pyrotechnics are expected to produce an aerosol for which condensation due to hygroscopic growth is slight. Thus, evaluation of the pyrotechnics at ~40% RH approaches an assessment of the nominal aerosol. The NWC 90 and NWC 164 aerosols appear to provide greater extinction at wavelengths >7 μm, and comparable visible wavelength extinction, relative to the other formulations. As described earlier, the NWC 90 and NWC 164 pyrotechnics differ from the others in that graphite was added to the mix. It appears, therefore, that absorption of radiation at wavelengths >7 μm by the graphite particles may have resulted in the observed increased extinction. However, as these measurements are near the sensitivity threshold of the transmissometer, a definite conclusion cannot be drawn at this time.

Extinction Effectiveness at Moderate Humidity (∿75% RH)

Figure 3 presents the extinction, yield, and aerosol growth data for the pyrotechnics at 73-76% RH. For these alkali-halide salt aerosols, of which NaCl and KCl are primary components, the humidity range of 70-80% RH is critical in terms of deliquescent aerosol growth. Pure NaCl deliquesces at ∿75% RH and KCl at ∿83% RH. Through the judicious mixing of these two salts, and the addition of small quantities of LiCl, the Naval Weapons Center has attempted to enhance the overall deliquescent growth of the resultant aerosol. The six pyrotechnics being evaluated represent attempts to determine the optimum mixing proportion of these salts. At 75% RH, therefore, it was expected that differences in the aerosol growth characteristics would be manifested in measurable differences in extinction. As seen in Figure 3, significant differences do appear between the extinction spectra (Note that the NWC 29 aerosol (Label #2) is at 76% RH whereas the other spectra are at 75% RH).

The most significant difference in aerosol extinction effectiveness is that, relative to CY85A, the other aerosols provide approximately two to four times greater extinction at nearly all wavelengths. Examination of the aerosol mass growth factor reveals that for 73-76% RH, the CY85A aerosol has a growth factor of ∿1.6 whereas the other aerosols have a value of ∿3.1. This clearly indicates that the greater extinction provided by the other pyrotechnics, relative to CY85A, is due to enhanced aerosol growth characteristics. As aerosol growth is highly dependent upon humidity in this critical 70-80% RH range, additional tests will have to be performed to determine if the extinction differences among the other aerosols is significant.

Thus, given that all the pyrotechnics provide the same nominal mass yield as discussed earlier, extinction at 75% RH may be increased by approximately a factor of 2 to 4 over that provided by CY85A through the use of any of the other five pyrotechnics.

Extinction Effectiveness at High Humidity (90% RH)

Figure 4 presents the extinction, yield, and aerosol growth data for the pyrotechnics at ∿90% RH. At this humidity, all of the aerosols are expected to have undergone complete deliquescence and exist as liquid solution droplets (with the exception of the graphite component of the NWC 90 and NWC 164 aerosols since graphite is not deliquescent). The relative humidity for these tests ranged from 88% for CY85A to 92% for NWC 29. Since aerosol growth, and hence extinction, is highly humidity dependent at these high humidities (resulting in increased extinction as humidity increases), the humidity corresponding to each of the extinction spectra must be considered. Hence, the relative positioning of the spectra may be due entirely to variations in humidity and not represent actual differences in aerosol extinction effectiveness.

Thus, at ∿90% RH, it presently appears that all the pyrotechnics provide approximately the same degree of extinction effectiveness having comparable nominal mass yields and mass extinction coefficients at all wavelengths (0.5-14 μm); however, an additional measurement of the CY85A aerosol IR extinction at 90% RH (not 88% RH as here) would be prudent to verify its effectiveness.

Section 4
INVESTIGATION OF THE DELIQUESCENCE OF PURE AND MIXED SALTS

4.1 Introduction

The deliquescent growth properties of many pure salt aerosols are reasonably well-known and documented in the literature. However, much less is known on the growth characteristics of aerosols consisting of two or more salt components. Tang (1976), has shown that the initial deliquescence humidity for a two component salt aerosol is lower than the deliquescence humidity of either of the pure salts. Additionally, if the two salts are mixed at the proper proportion, referred to as the eutonic mixture, the mixed aerosol will completely dissolve upon deliquescence; at other proportions, deliquescence will begin at the same humidity as the eutonic mixture but complete dissolution will not occur until a higher humidity is reached.

To aid the Navy in the determination of the optimum mixture for improved deliquescent growth of certain alkali-halide salts, a laboratory study was undertaken to evaluate the growth characteristics of 22 pure and mixed salts. The procedure used (detailed in Hanley and Mack, 1980) provides for observation of the growth of microscopic salt particles under controlled humidity conditions. The particles, observed through a microscope, were 20-40 μm in diameter and were mounted upon stretched spider thread filaments of approximately 1 μm diameter. Humidity measurements were obtained with an EG&G "Dew All" humidity analyzer (a chilled mirror dew point device) and in-line wet and dry bulb therometers.

4.2 Salt Selection and Sample Preparation

Table 4 presents a list of the salts evaluated and summarizes their deliquescent growth characteristics. The authors gratefully acknowledge the assistance of Dr. Larry Mathews, NWC China Lake, for his assistance in the salt selection procedure. Twelve of the salts selected were recommended by NWC to aid in the development of a $MgCl_2$ smoke and to evaluate the deliquescent growth of two smokes recently developed at NWC.

Table 4

Observations on the Growth of Pure and Mixed Salt Particles

		Relative Humidity at which the Following Occurred		
		Condensation Detected	Significant Growth	Complete Dissolution
A. PURE SALTS				
MIX #1	$AlCl_3$	- UNABLE TO OBTAIN INITIAL DRY STATE -		
2	LiCl	11%	11%	11%
3	$MgCl_2$	33	33	33
4	NaI	35	35	37
5	NaCl	77	77	77
6	KCl	87	87	87
7	Na_2CO_3	~92	~92	~92
B. RECENTLY DEVELOPED NWC SMOKES				
MIX #8	55.8% NaCl, 24% KI, 15.9% KCl, 4.3% LiCl	(37)*	55	74
9	45.9% NaCl, 25.8% Na_2CO_3, 24.2% KCl, 4.1% LiCl	(69)	69	91
C. EUTONIC MIXTURES				
MIX #10	64% NaCl, 36% KCl	75	75	76
11	97.2% $MgCl_2$, 2.8% NaCl	34	34	39
12	97.2% $MgCl_2$, 2.8% NaI	34	34	35
13	90% $MgCl_2$, 10% NaI	33	34	34
D. MIXTURES CONTAINING SMALL QUANTITIES OF LiCl				
MIX #14	95% $MgCl_2$, 5% LiCl	(29)	32	33
15	95% $NaCl_2$, 5% LiCl	(11)	67	77
16	92.4% $MgCl_2$, 5% LiCl, 2.6% NaI	(27)	32	34
17	61% NaCl, 34.2% KCl, 4.8% LiCl	(71)	72	75
E. $MgCl_2$ - NaCl SERIES OF MIXTURES				
MIX #18	83% $MgCl_2$, 17% NaCl	33	34	64
19	67% $MgCl_2$, 33% NaCl	34	34	73
20	50% $MgCl_2$, 50% NaCl	35	35	76
21	33% $MgCl_2$, 67% NaCl	33	50	77
22	17% $MgCl_2$, 83% NaCl	33	77	77

*See text for explanation of values in parenthesis.

The salts are divided into five groups. The first group contains pure salts which were evaluated for comparison to their mixtures. The next group represents the expected aerosol composition of the two recently developed NWC pyrotechnics. The group of eutonic mixtures was aimed at assessing the advantages of generating an aerosol of a eutonic salt mixture. The addition of small quantities of LiCl, which deliquesces at 11% RH, to salts of higher deliquesce humidities, was examined for four salts. The final group of salts were selected to provide general information on the growth of a two component salt aerosol.

The salt samples were prepared by first dissolving five grams of the specified mixture in ∿100 ml of distilled water. Samples were then collected upon spider thread filaments by directing a fine mist of the salt solution over the thread with some of the droplets striking and remaining on the thread.

The thread mounted particles were then placed in the viewing chamber of the apparatus. The humidity was reduced to ∿5% RH to bring the particle to its dry state. However, due to hysteresis effects, many of the salts, including most of the $MgCl_2$ mixtures, once wetted, would not dry out even when exposed to 5% RH for several hours. In these cases, a heated air stream of ∿110°C was momentarily passed over the particle to obtain the desired dry, solid salt particle.

Having attained the initial dry salt, the humidity was increased in a step-wise fashion with constant observation of the particle's appearance and size. Observations were made under conditions of increasing humidity from ∿5-95% RH. The accuracy of the humidity measurement and control is estimated to be within ±2% RH based on the observed deliquescent humidity of the pure salts and on the repeatability of the measurements (see Hanley and Mack, 1980 for details). An investigation of hysteresis effects, which occur upon decreasing humidity, was not within the objective of this study.

4.3 Results of the Deliquescence of Pure and Mixed Salts

Table 4 summarizes the deliquescent growth characteristics of the evaluated salts. Tabulated are:

1) The humidity at which condensation was first detected on the salt particle. Typically, for the mixed salts, this was observed as a slight rounding of a previously sharp edge or, a bright spot, caused by the microscope light striking the particle, in what was previously a dull area. Though detected, actual growth due to this initial condensation was often negligible.

2) The humidity at which significant growth occurred. At this stage, in the growth of most of the mixed salts, the particle had a complete water coating over remaining undissolved salt.

3) The humidity at which the particle completely dissolves. By this stage, the particles were near perfect spheres and sufficiently transparent to verify that all the salt had dissolved.

Note that for the salts containing ~5% LiCl (salts #8, 9, and 14-17) the humidity at which condensation was detected ranged from 11 to 71% RH. It is suspected that for all of these salts, condensation may have actually begun at ~11% RH but went undetected, due to the relatively small quantities of LiCl involved, until a higher humidity was reached. Therefore, these values are placed in parentheses.

Pure Salts

With the exception of $AlCl_3$, the deliquescence humidity of each of the pure salts was within 2% RH of values typically stated in the literature (e.g., Low, 1969). Due to its chemical reaction with water, (forming, in general, HCl and AlOH) the sample preparation procedure was inappropriate for $AlCl_3$. As indicated, the resulting $AlCl_3$ solution remained liquid even when exposed to prolonged periods of low humidity and heating.

Eutonic Salt Mixtures

Salts 10-13 were evaluated for comparison of the growth of two-component eutonic salt mixtures to the growth of the pure salt of the

mixture having the lower deliquescence humidity. Thus, the growth of the NaCl-KCl eutonic mix is to be compared to the growth of pure NaCl, and the $MgCl_2$ - NaCl and $MgCl_2$ - NaI eutonic mixes to pure $MgCl_2$. The exact eutonic proportions for an $MgCl_2$ - NaI mixture is unknown and thus, salts 12 and 13 represent estimations of the eutonic proportions.

The NaCl - KCl eutonic mixture showed a slightly lower deliquescence humidity of 75% RH as compared to 77% RH for pure NaCl. The $MgCl_2$ eutonic mixtures, however, did not show any lowering of the deliquescence humidity relative to pure $MgCl_2$. Both these findings are consistent with those of Tang (1976) who measured an approximate 1.5% RH decrease in the deliquescence humidity of a eutonically-mixed NaCl -KCl aerosol relative to pure NaCl, and further stated that the deliquescence humidity of a $MgCl_2$ - NaCl eutonic mix would be "very close" to the deliquescence humidity of pure $MgCl_2$.

Thus, for the salts evaluated, there appears to be little advantage in attempting to generate an aerosol of these eutonic salt mixtures. This limited evaluation does not, of course, rule out the possibility that eutonic mixtures involving other salts may be more advantageous.

Salts Containing Small Quantities of LiCl

Each of the salts of this group (salts 14-17) may be compared to a corresponding salt minus the LiCl component. Specifically, comparisons may be made between salts 14 and 3, 15 and 5, 16 and 12, and 17 and 10. As noted earlier, due to the small proportion of LiCl involved, condensation may have gone undetected in these salts until a humidity substantially greater than the initial deliquescence humidity was reached.

For each salt (14-17) significant growth was observed at a lower humidity than for the corresponding salt without the LiCl component. The greatest effect was observed in the 95% NaCl - 5% LiCl sample where significant growth was observed at 67% RH as opposed to 77% RH for pure NaCl.

Thus, the addition of ~5% LiCl to a primarily NaCl aerosol appears beneficial, reducing the humidity at which significant growth commences.

$MgCl_2$ - NaCl System

Salts 18-22, along with the eutonic mixture (Salt 11), represent a systematic investigation of the two component $MgCl_2$ - NaCl salt system. As can be seen, within the accuracy of the measurements, all these salts commenced condensation at the same humidity as the deliquescence humidity for pure $MgCl_2$ (33% RH). The humidity required for the salts to completely dissolve increased from 39 to 77% RH as the proportion of NaCl increased from 2.8 to 67%. Since this relationship is monotonic, the humidity required for complete dissolution of salt mixtures of other proportions of NaCl and $MgCl_2$ may be readily predicted.

4.4 Suggestions for Future Investigation of the Deliquescence of Pure and Mixed Salts

The analyses procedure used in the study to evaluate the selected salts provided a means of determining the salt's deliquescence humidity. However, quantitative measurements of how much a salt particle grew upon deliquescence were not possible due entirely to the difficulties of measuring the initial size of the dry salt sample. In their dry state, most of the salts, particularly the mixed salts, were too irregularly shaped for an accurate, repeatable size measurement. (However, accurate size measurements are obtained after the particle has sufficiently deliquesced to have a smooth shape). Thus, how the pure salts performed relative to their various mixtures in terms of actual growth upon and after deliquescence was not assessed.

A procedure which could provide quantitative growth measurements involves measuring the mass increase of a salt sample through use of a humidified microbalance. Such measurements have been made by Winkler and Junge (1972), and a similar procedure was developed at Calspan for assessment of ambient aerosol samples (see Mack et al, 1981).

Simultaneous measurement of a salt sample's growth using both the visual microscopic technique and mass microbalance technique would clearly define the deliquescent growth characteristics of the salt sample. A limited effort was applied to obtaining these simultaneous measurements during this study, however, difficulties were encountered due to prolonged equilibration times (hours) required for the mass samples. These long equilibration times were attributed to the relatively large size of the particles making up the mass sample as compared to the ∿30 μm diameter thread mounted particles. While contractual limitations precluded resolution of this problem during this year's effort, it is believed worthy of further investigation in the future.

Section 5
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The major findings realized from this year's effort are:

1. At ≥40% RH, the NWC 90 and NWC 164 pyrotechnics appear to provide greater extinction at IR wavelengths longer than 4.7 μm relative to the other pyrotechnics. This performance may be due to the graphite component of the NWC 90 and NWC 164 aerosols. Additional tests are required before a definite conclusion may be drawn.

2. At ≥75% RH, extinction produced by NWC 29, NWC 78, NWC 79, NWC 90 and NWC 164 is approximately a factor of four greater than that provided by CY85A. This is attributed to greater aerosol growth of the other pyrotechnics relative to CY85A.

3. At ≥90% RH, all six pyrotechnics provide approximately the same degree of extinction effectiveness.

4. The nominal mass yields for the six pyrotechnics appear equivalent. Values ranged from 28 to 37%, and were apparently payload dependent with greater yields measured for larger payloads.

5. Based on SEM analyses of individual particles in the size range 0.2 to 1.0 μm, no evidence was seen supporting a significant particle size-chemical composition relationship for the evaluated pyrotechnics.

6. The eutonic mixture of $MgCl_2$ - NaCl and the estimated eutonic mixtures of $MgCl_2$ - NaI provided no decrease in the deliquescence humidity relative to the deliquescence humidity of pure $MgCl_2$.

7. The eutonic mixture of NaCl - KCl provided a 2% RH decrease in the humidity at which deliquescence began relative to pure NaCl.

Recommendations

Based on the results of this study and our previous work, we believe that significant improvement in the extinction performance of pyrotechnically-generated alkali-halide smokes over that of the current NWC pyrotechnics is possible. The two most promising approaches to achieve this improvement appear to be through (1) lowering the deliquescence humidity of the aerosol and (2) increasing the pyrotechnic's dry yield. Both approaches have been recommended by Calspan in the past and are recognized by NWC.

As has been shown in our past reports, the CY85A aerosol begins to deliquesce at ∿70% RH; up to this humidity, extinction is at a relative minimum and does not vary substantially with humidity. At humidities exceeding 70%, extinction is humidity dependent, increasing with increasing humidity. NWC has recently developed a magnesium-perchlorate-based pyrotechnic which is expected to produce an aerosol which deliquesces at ∿33% RH. Extinction resulting from this new pyrotechnic formulation should, therefore, become humidity dependent at ∿33% RH, and a significant increase in extinction, relative to that from CY85A, is expected over the RH range from ∿33 to ∿80%. This formulation should be tested in large scale laboratory experiments.

The nominal yield of all the tested NWC pyrotechnics is ∿35%. The remainder of the material exists in the gas phase and as non-aerosolized residue. (Limited measurements suggest that unburned residue may amount to

as much as 25% of payload weight). Clearly, the extinction performance would be improved if the nominal yield could be increased. NWC is presently attempting to increase the dry yield through altering the salt to binder ratio of the pyrotechnic and through use of more energetic pyrotechnic binders.

A major factor affecting the ultimate utilization of the alkali-halide pyrotechnics is how well they perform relative to the standard phosphorus screens now deployed. Thus, a comprehensive comparison of the alkali-halide pyrotechnics to the phosphorus pyrotechnics should be made. A limited comparison of the alkalide-halide pyrotechnics to pure white phosphorus is presented in Appendix B. However, the representativeness of a WP smoke produced from laboratory-grade white phosphorus to an actual phosphorus pyrotechnic aerosol is unknown. Additionally, an assessment must be made of the nominal yield of the actual phosphorus pyrotechnics; it is likely that the yield of, say, a phosphorus felt wedge is significantly less than that of the pure white phosphorus payloads used in our tests.

Based on the above conclusions and information, it is recommended that future study include the following:

1. Evaluation of the extinction characteristics of NWC's recently developed magnesium-perchlorate-based pyrotechnic. The evaluation should include, as a function of humidity, measurements of visible and IR wavelength extinction, nominal mass yield and aerosol size distribution.
2. Development of pyrotechnic formulations which produce greater nominal mass yields than the present alkali-halide pyrotechnics.
3. Evaluation of the pyrotechnic nominal mass yield for payload masses comparable to the mass anticipated under actual deployment.
4. A comprehensive comparison of the extinction and yield characteristics between the alkali-halide and phosphorus pyrotechnics.
5. Quantification of the deliquescent growth of salt mixtures through simultaneous microscopic observation and microbalance mass measurements.

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APPENDIX A

EXTINCTION AND MASS YIELD PARAMETERS

There are numerous parameters which may be used to characterize the extinction effectiveness of an obscurant. Which parameter, or combination of parameters, is chosen will depend upon the specific applications involved. In our past reports, the extinction performance of the NWC pyrotechnics has been reported in terms of extinction per unit payload mass. Thus, the effects of 1) dissemination efficiency and 2) aerosol extinction were combined in a single parameter.

In the development of an obscurant, it is often desirable to separate the effects of dissemination efficiency and aerosol extinction. By doing so, each phase may be evaluated, studied and improved separately. Additionally, this allows for comparison to other obscurants which may differ fundamentally in the means of dissemination and/or aerosol properties.

When discussing hygroscopic aerosols, confusion sometimes occurs with reference to "aerosol mass" as to whether this is to include mass resulting from processes such as oxidation, hydration and condensation or, is solely the mass of the aerosol which originated from the pyrotechnic. To avoid this confusion in this report, the term "total aerosol mass" will refer to the entire aerosol mass. The term "nominal aerosol mass" will refer only to the aerosol mass which originated directly from the pyrotechnic and will not include, therefore, any additional mass as may be supplied by the environment. Thus, for the alkali-halide aerosols, the nominal mass is the total aerosol mass minus the mass of condensed water; for a phosphorus smoke aerosol, the nominal mass would be the total aerosol mass minus the mass due to oxidation, hydration and condensation.

In light of the above, extinction measurements are reported in terms of both a dissemination efficiency and an aerosol extinction parameter. Dissemination efficiency is presented in terms of the pyrotechnic nominal mass yield computed from

$$\text{NOMINAL MASS YIELD} = (\text{NOMINAL AEROSOL MASS})/(\text{PAYLOAD MASS}).$$

Extinction measurements are presented in terms of the nominal mass extinction coefficient computed from

$$\text{NOMINAL MASS EXTINCTION COEFFICIENT} = \frac{\text{(EXTINCTION COEFFICIENT)}}{\text{(NOMINAL AEROSOL MASS PER UNIT CLOUD VOLUME)}}$$

(where the extinction coefficient is obtained from Beer's Law, $I=I_o e^{-\beta x}$).* Thus, the extinction coefficient is normalized by the mass concentration of only the material which originates from the pyrotechnic. This parameter provides a means of ranking the extinction effectiveness of different aerosols. For the convenience of those who prefer to relate extinction directly to payload, Appendix C presents the payload mass extinction coefficient computed from

$$\text{PAYLOAD MASS EXTINCTION COEFFICIENT} = \frac{\text{(EXTINCTION COEFFICIENT)}}{\text{(PAYLOAD MASS PER UNIT CLOUD VOLUME)}}$$

Clearly, the payload mass extinction coefficient is mathematically equal to the product of the nominal mass yield and nominal mass extinction coefficient.

When dealing with a deliquescent aerosol, where particle size and, hence, extinction, is a function of humidity, a measure of the aerosol growth is useful in interpreting the extinction data. Aerosol growth will be represented by the aerosol mass growth factor computed from

AEROSOL MASS GROWTH FACTOR = (TOTAL AEROSOL MASS)/(NOMINAL AEROSOL MASS).

Also, the added mass due to condensation will increase the total mass yield of the pyrotechnic. This is reported as the pyrotechnic total mass yield computed from

TOTAL MASS YIELD (@ RH) = (TOTAL AEROSOL MASS (@ RH))/(PAYLOAD MASS).

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*The terms "nominal mass extinction coefficient" and "total mass yield" as used here, are believed to be equivalent to Tarnove's (1979) "overall yield factor" and "obscuration figure-of-merit of the second order", respectively.

APPENDIX B

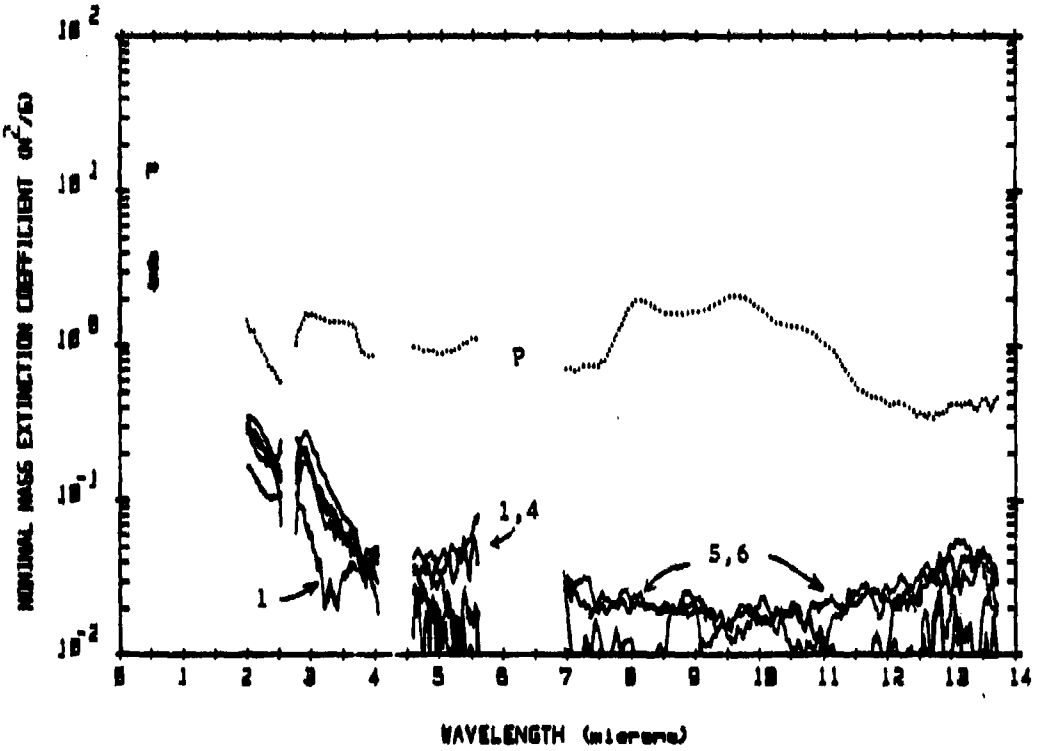
A LIMITED COMPARISON OF ALKALI-HALIDE AND PHOSPHORUS SMOKES

Figures B-1 and B-2 present a comparison of the extinction effectiveness of the alkali-halide smokes to a phosphorus smoke at ∿40 and 90% RH. The payloads used in the phosphorus tests were purified laboratory grade white phosphorus. Unlike the alkali-halide smokes for which the mass loading samples were baked and reweighed to measure the nominal aerosol mass, the nominal aerosol mass of the phosphorus smokes was calculated by dividing the total aerosol mass (as measured by mass loading filter samples) by the assumed phosphorus aerosol mass growth factor as given by Tarnove (1979)*.

An can be seen in the figures, at ∿40% RH, the nominal mass extinction coefficient for phosphorus ranges from ∿10 to 100 times greater than that for the alkali-halide smokes. This is not unexpected as the alkali-halide aerosols have not undergone significant deliquescence at this humidity. At 90% RH, where complete deliquescence has occurred for all the smokes, the performance of the alkali-halides approaches, and at times may equal, that of phosphorus at wavelengths from about 0.5-4 μm and 12-14 μm.

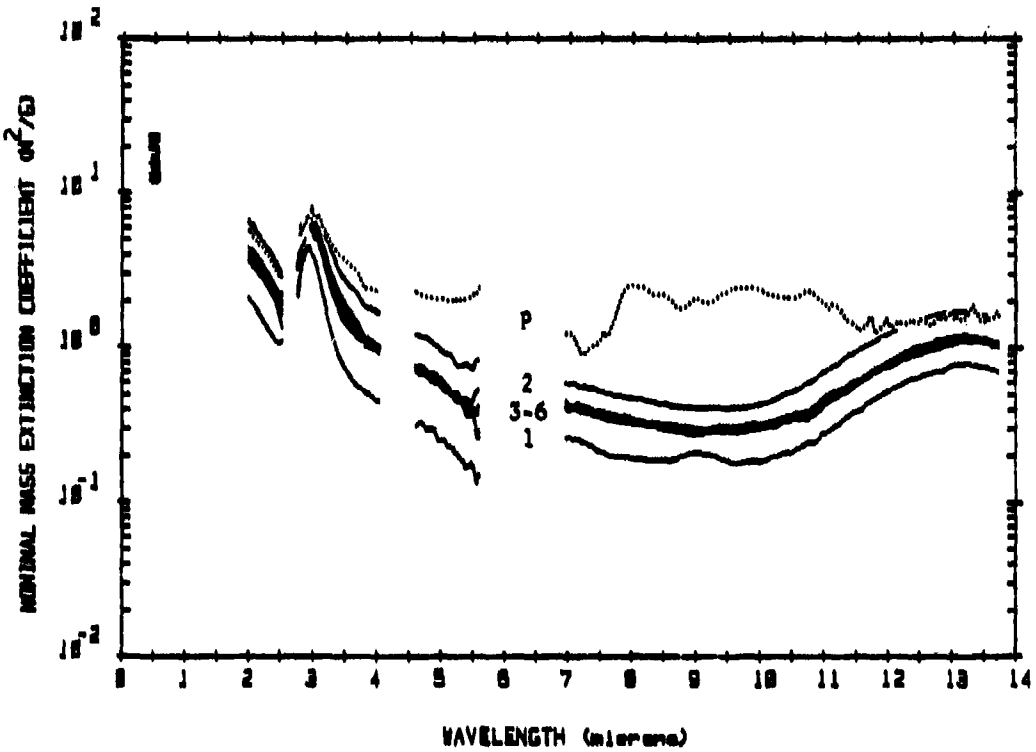
As laboratory grade white phosphorus was used in these tests, as opposed to actual munition material as for the alkali-halides, a discussion of extinction relative to the payload mass is inappropriate for these tests. It is interesting to note, however, that the nominal mass yields for the phosphorus payloads were calculated to be 70% and 84%, significantly less than the near 100% frequently assumed.

*When discussing phosphorus smokes, the term "aerosol mass growth factor" as used here is believed to be equivalent to Tarnove's "intrinsic yield factor." For the alkali-halide smokes, which may contain a non-hygroscopic component, the equivalence of these two terms is uncertain.



Test No.	Payload	Label	Material	RH	Pyrotechnic Nominal Mass Yield	Pyrotechnic Total Mass Yield @ RH	Aerosol Mass Growth Factor
20	160 g	#1	CY85A	48%	37%	37%	1.00
24	160 g	#2	NWC 29	42%	36%	37%	1.04
25	160 g	#3	NWC 78	37%	36%	37%	1.03
23	160 g	#4	NWC 79	37%	34%	35%	1.03
22	160 g	#5	NWC 90	46%	35%	37%	1.06
21	160 g	#6	NWC 164	44%	36%	37%	1.04
18	80 g	No IR Data	CY85A	37%	30%	30%	1.00
19	80 g	No IR Data	CY85A	34%	31%	31%	1.00
-	22.5 g	P WHITE PHOSPHORUS		40%	84%	329%	3.9

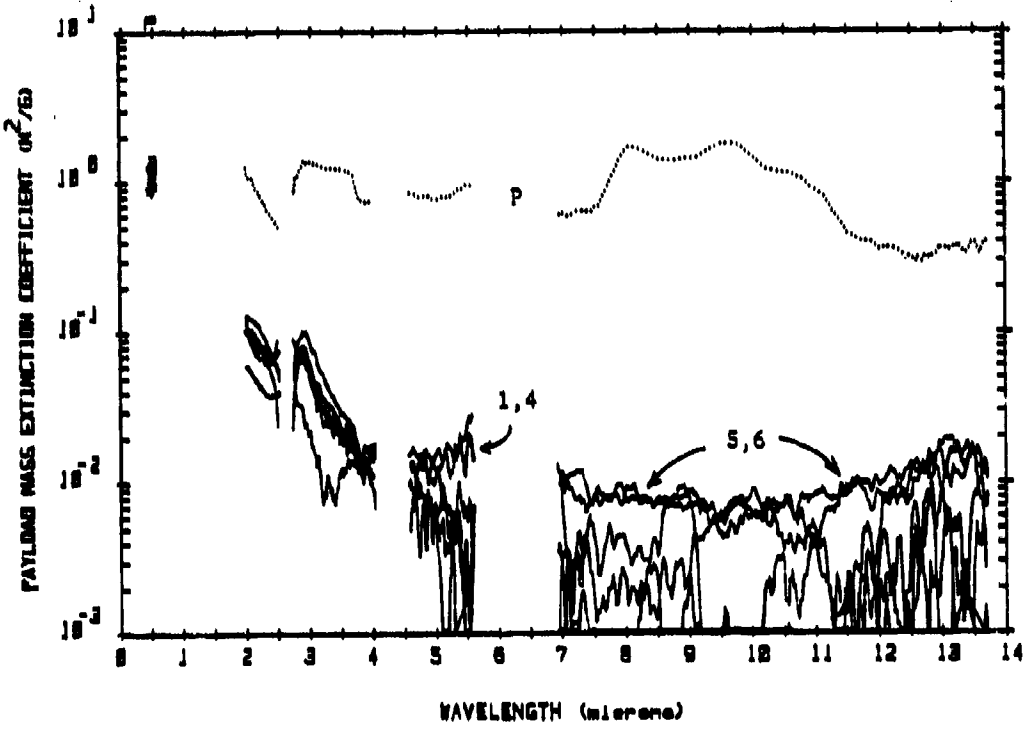
Figure B-1. Comparison of the Extinction Characteristics of the NWC Pyrotechnics to White Phosphorus at ∿40% RH.



Test No.	Payload	Label	Material	RH	Pyrotechnic Nominal Mass Yield	Pyrotechnic Total Mass Yield @ RH	Aerosol Mass Growth Factor
3	80 g	#1	CY85A	88%	34%	123%	3.62
7	80 g	#2	NWC 29	92%	32%	219%	6.84
8	80 g	#3	NWC 78	91%	28%	151%	5.39
6	80 g	#4	NWC 79	90%	29%	161%	5.55
5	80 g	#5	NWC 90	89%	37%	174%	4.70
4	80 g	#6	NWC 164	90%	33%	158%	4.79
-	11.25 g	P	WHITE PHOSPHORUS	91%	70%	560%	8.0

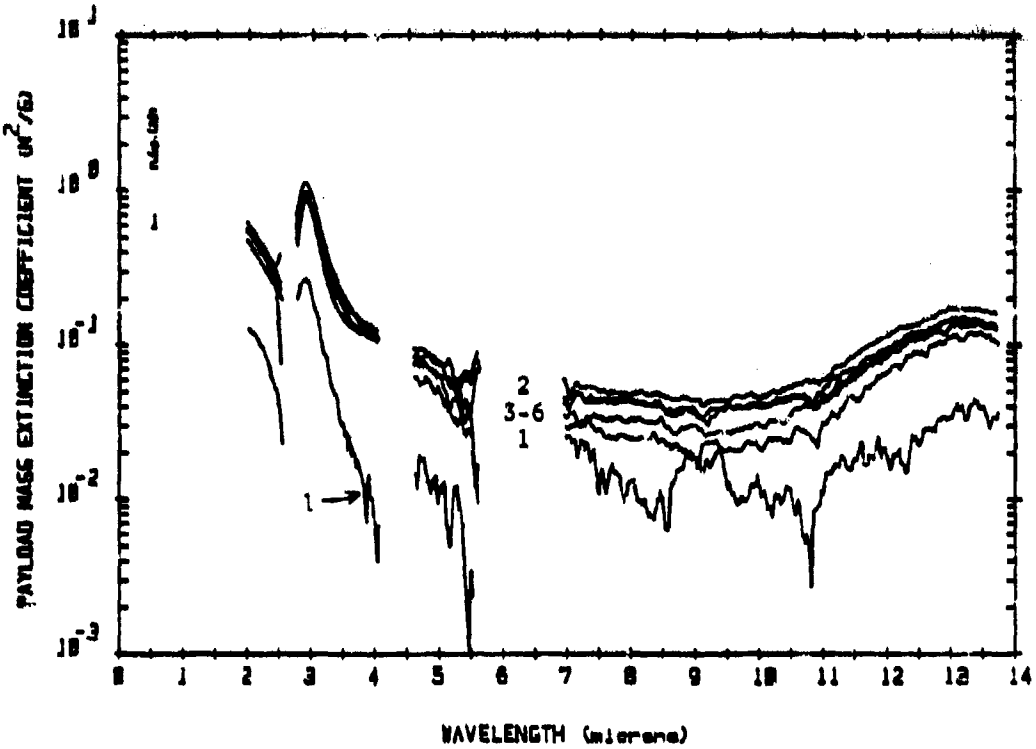
Figure B-2. Comparison of the Extinction Characteristics of the NWC Pyrotechnics to White Phosphorus at ∿90% RH.

APPENDIX C
PAYLOAD MASS EXTINCTION COEFFICIENTS



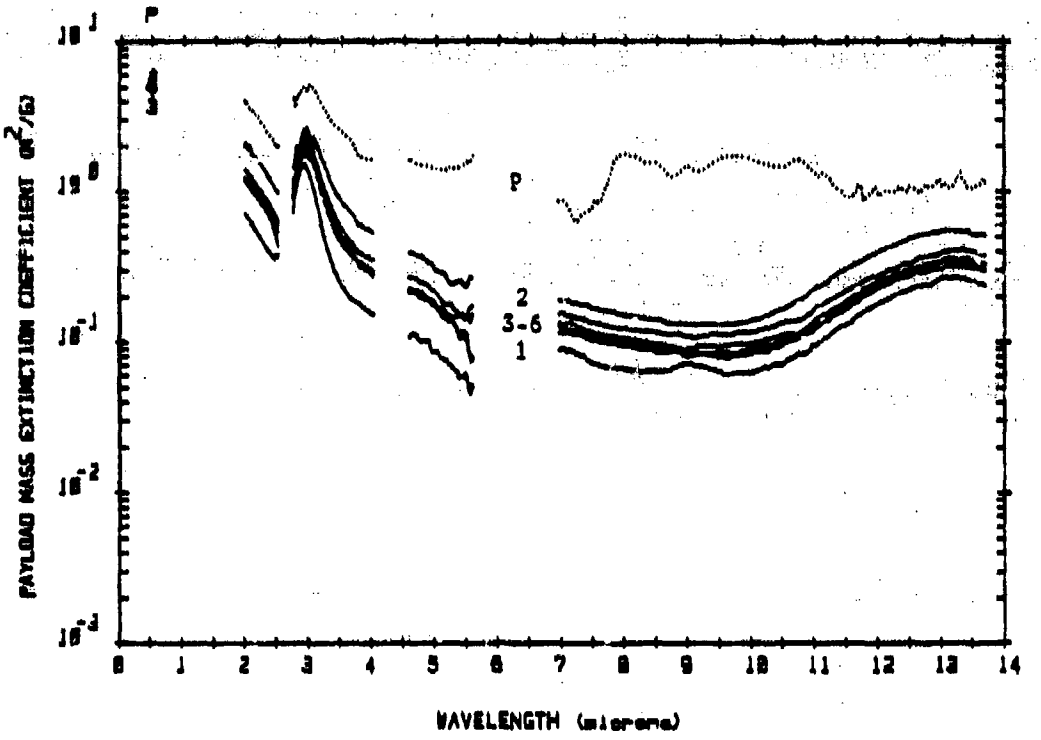
Test No.	Payload	Label	Material	RH	Pyrotechnic Nominal Mass Yield	Pyrotechnic Total Mass Yield @ RH	Aerosol Mass Growth Factor
20	160 g	#1	CY85A	48%	37%	37%	1.00
24	160 g	#2	NWC 29	42%	36%	37%	1.04
25	160 g	#3	NWC 78	37%	36%	37%	1.03
23	160 g	#4	NWC 79	37%	34%	35%	1.03
22	160 g	#5	NWC 90	46%	35%	37%	1.06
21	160 g	#6	NWC 164	44%	36%	37%	1.04
18	80 g	No IR Data	CY85A	37%	30%	30%	1.00
19	80 g	No IR Data	CY85A	34%	31%	31%	1.00
-	22.5 g	P WHITE PHOSPHORUS		40%	84%	329%	3.9

Figure C-1. Extinction Characteristics of the NWC Pyrotechnics and White Phosphorus at ~40% RH.



Test No.	Payload	Label	Material	RH	Pyrotechnic Nominal Mass Yield	Pyrotechnic Total Mass Yield @ RH	Aerosol Mass Growth Factor
10	80 g	#1	CY85A	75%	30%	48%	1.60
14	80 g	#2	NWC 29	76%	29%	106%	3.66
15	80 g	#3	NWC 78	75%	30%	94%	3.13
17	80 g	#4	NWC 79	75%	29%	88%	3.03
12	80 g	#5	NWC 90	75%	34%	102%	3.00
11	80 g	#6	NWC 164	75%	31%	93%	3.00
9	80 g	Overlaps #1	CY85A	73%	32%	49%	1.53
16	160 g	Overlaps #1	CY85A	76%	35%	58%	1.66
13	80 g	No IR Data	NWC 79	75%	30%	95%	3.17

Figure C-2. Extinction Characteristics of the NWC Pyrotechnics at ∿75% RH.



Test No.	Payload	Label	Material	RH	Pyrotechnic Nominal Mass Yield	Pyrotechnic Total Mass Yield @ RH	Aerosol Mass Growth Factor
3	80 g	#1	CY85A	88%	34%	123%	3.62
7	80 g	#2	NWC 29	92%	32%	219%	6.84
8	80 g	#3	NWC 78	91%	28%	151%	5.39
6	80 g	#4	NWC 79	90%	29%	161%	5.55
5	80 g	#5	NWC 90	89%	37%	174%	4.70
4	80 g	#6	NWC 164	90%	33%	158%	4.79
-	11.25 g	P	WHITE PHOSPHORUS	91%	70%	560%	8.0

Figure C-3. Extinction Characteristics of the NWC Pyrotechnics and White Phosphorus at ~90% RH.